1.1 Products of Combustion Reactions

Working as a team in a local dogsled race, Kayla and her dogs challenge the cold and their physical limits. They are all working and breathing hard. With each breath Kayla and her dogs take, they must exhale the products of **cellular respiration**—a process that converts the chemical potential energy within food into a form the body's muscles can use. Energy-converting processes, like cellular respiration and the **combustion** of fuels, are important; however, they produce emissions.

In the next investigation you will look at the chemical properties of the gases produced from cellular respiration and from the combustion of a hydrocarbon.

cellular respiration: the process by which cells convert the chemical energy stored in organic molecules (sugars) into energy that cells can use

combustion: a chemical reaction that occurs in the presence of oxygen and results in the release of energy

Investigation

Comparing the Effects of the Products of Cellular Respiration and Combustion

Cells use molecules within food as an energy source. Cellular respiration is a process similar to the combustion of hydrocarbons in that oxygen is required, carbon dioxide and water are produced, and energy is released.

Science Skills
- ✓ Performing and Recording
- ✓ Analyzing and Interpreting

Purpose

You will compare the effects of the products of cellular respiration with the products of the combustion of a hydrocarbon (coal).

Part 1: Cellular Respiration

Materials

- 125-mL Erlenmeyer flask
- 75 mL of distilled water
- bromothymol blue indicator
- 100-mL graduated cylinder
- drinking straw
- eyedropper
- stopwatch

CAUTION!
Use gloves, safety glasses, and a lab apron for this activity.

Procedure

step 1: Use the graduated cylinder to measure 75 mL of distilled water; then transfer the water to the Erlenmeyer flask.

step 2: Add four drops of bromothymol blue to the distilled water. Note the colour of the mixture.

step 3: Insert the drinking straw into the mixture in the flask, and exhale through the straw until the colour of the indicator changes to yellow. Record the time taken for the indicator to change colour.

Observations

1. Complete the following table.

Colour of Indicator Before Exhaling	Time Taken for Indicator to Turn Yellow

Analysis

2. Explain the significance of the colour change.
3. Identify the reason for the mixture to change colour. **Note:** Refer to the "Acid-Base Indicators" table on page 184.
4. Write the balanced chemical equation for the cellular respiration of glucose, $C_6H_{12}O_6(aq)$.
5. Hypothesize the effect that carbon dioxide released by many processes could have on water within the biosphere.

Part 2: Teacher Demonstration—Combustion of Coal

Materials

Your teacher will set up the materials as shown in Figure B1.1.

CAUTION!
Be careful near an exposed flame and hot objects.

Figure B1.1

Procedure for Teacher

step 1: Measure 75 mL of distilled water, and transfer it to the flask.

step 2: Add four drops of bromothymol blue to the distilled water. Note the colour of the mixture.

step 3: Place the coal in a crucible, and ignite the coal using a Bunsen burner or torch.

step 4: Once the coal is glowing and producing smoke, position the crucible below the inverted funnel.

step 5: Turn on the vacuum to draw the smoke into the flask. Record the time it takes for the indicator inside the flask to change colour.

step 6: Turn off the vacuum, and let the system sit untouched for a few minutes to allow the air pressure in the flask to return to normal. Remove the crucible, and extinguish the coal with water.

Observations

6. Complete the following table.

Colour of Indicator Before	Time Taken for Indicator to Turn Yellow

Analysis

7. Explain the significance of the colour change.
8. Suggest a reason why the water containing the bromothymol blue indicator in Parts 1 and 2 took different lengths of time to change colour.
9. Write the balanced chemical equation for the combustion of coal, C(s).
10. Identify a process or technology where coal is used.

Combustion Reactions and Their Products

Natural gas used to heat most homes contains mostly methane, $CH_4(g)$, and is an example of a **hydrocarbon** and a **fuel**. During combustion, collisions between the molecules of methane and oxygen result in the formation of new molecules.

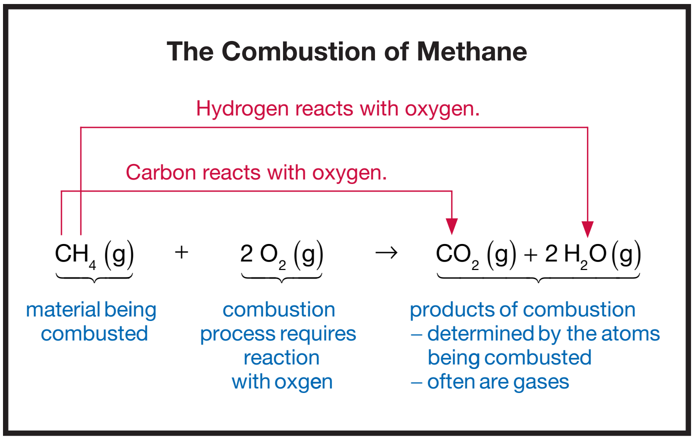


Figure B1.2

The equation in Figure B1.2 shows that the products of combustion are carbon dioxide, $CO_2(g)$, and water vapour, $H_2O(g)$—oxides of carbon and hydrogen.

The products formed during a combustion reaction are directly related to the atoms present in the substance being combusted. When a hydrocarbon combusts, the products are usually carbon dioxide and water. Later, you will discover that other products can appear if other atoms appear within the fuel. During most combustion reactions, the oxides produced are released into the atmosphere. These are referred to as **emissions**.

- **hydrocarbon:** an organic compound containing only carbon and hydrogen atoms
- **fuel:** a substance that releases energy when involved in a chemical reaction (often combustion) or a nuclear reaction
- **emission:** a substance discharged into the atmosphere or into surface water

Balancing Chemical Equations

Substances do not always react with each other on a one-to-one basis. To indicate the relative proportions of each substance involved in a reaction, you need to balance the chemical equation. Matter is conserved in all chemical processes. Therefore, a balanced chemical equation has an equal number of each type of atom appearing on the reactants side and on the products side of the equation. Balance the equation using coefficients. Carefully work through Example Problem 1.1.

Example Problem 1.1

Ethane is one of the components in natural gas. Balance the following combustion equation for ethane.

$C_2H_6(g) + O_2(g) \rightarrow CO_2(g) + H_2O(g)$

Solution

$\underline{\quad\quad}\ C_2H_6(g) + \underline{\quad\quad}\ O_2(g) \rightarrow \underline{\quad\quad}\ CO_2(g) + \underline{\quad\quad}\ H_2O(g)$

↓ Add a coefficient to balance the carbon atoms.

$\underline{\ \mathbf{1}\ }\ C_2H_6(g) + \underline{\quad\quad}\ O_2(g) \rightarrow \underline{\ \mathbf{2}\ }\ CO_2(g) + \underline{\quad\quad}\ H_2O(g)$

↓ Add a coefficient to balance the hydrogen atoms.

$\underline{\ \mathbf{1}\ }\ C_2H_6(g) + \underline{\quad\quad}\ O_2(g) \rightarrow \underline{\ \mathbf{2}\ }\ CO_2(g) + \underline{\ \mathbf{3}\ }\ H_2O(g)$

↓ Add a coefficient to balance the oxygen atoms.

$\underline{\ \mathbf{1}\ }\ C_2H_6(g) + \underline{\ \mathbf{3.5}\ }\ O_2(g) \rightarrow \underline{\ \mathbf{2}\ }\ CO_2(g) + \underline{\ \mathbf{3}\ }\ H_2O(g)$

Recall that coefficients of 1 are not normally shown. Therefore, the balanced chemical equation is

$C_2H_6(g) + 3.5\ O_2(g) \rightarrow 3\ CO_2(g) + 4\ H_2O(g)$

Note: If you wish to have whole-number coefficients, multiply all coefficients in the equation by 2.

$\underline{\ \mathbf{2}\ }\ C_2H_6(g) + \underline{\ \mathbf{7}\ }\ O_2(g) \rightarrow \underline{\ \mathbf{4}\ }\ CO_2(g) + \underline{\ \mathbf{6}\ }\ H_2O(g)$

Practice

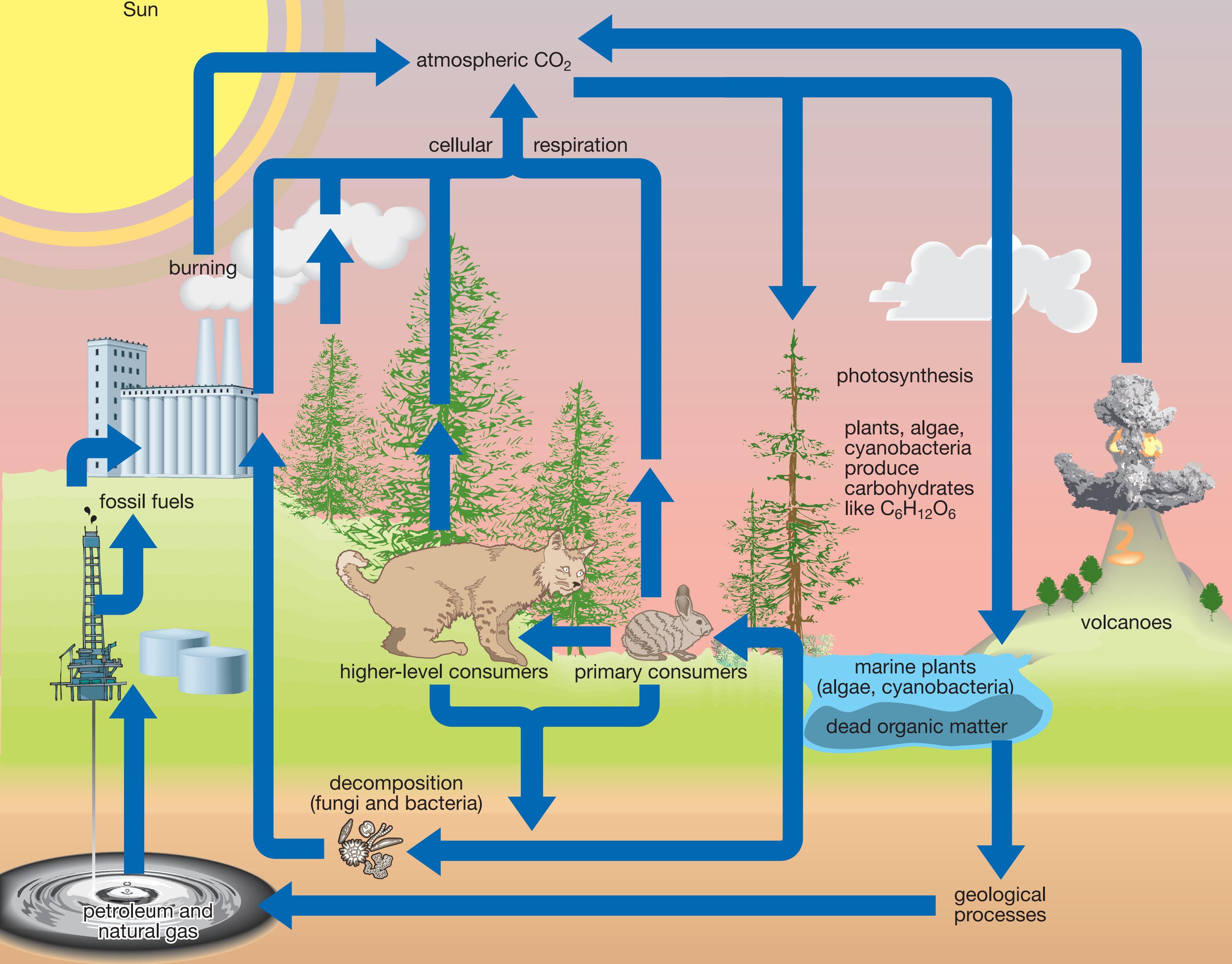
1. Balance the following combustion reactions.
   a. ___ $C_5H_{12}(l)$ + ___ $O_2(g)$ → ___ $CO_2(g)$ + ___ $H_2O(g)$
   b. ___ $C_4H_8(g)$ + ___ $O_2(g)$ → ___ $CO_2(g)$ + ___ $H_2O(g)$
   c. ___ $C_4H_{10}(g)$ + ___ $O_2(g)$ → ___ $CO_2(g)$ + ___ $H_2O(g)$
   d. combustion of octane, $C_8H_{18}(g)$

Oxides of Carbon

Burning carbon compounds, like wood and other forms of **biomass**, or burning hydrocarbon molecules, such as those present in natural gas and gasoline, results in the production of carbon dioxide. Within the biosphere, natural processes that produce carbon dioxide include the cellular respiration of organisms, forest fires, volcanic eruptions, and the weathering of some forms of rock. As a result of these natural processes, carbon dioxide is present within the collection of gases that make up Earth's atmosphere.

biomass: plant matter or agricultural waste from recently living sources used as a fuel or as an energy source

The Carbon Cycle



Recall from previous courses that carbon dioxide is an important gas with respect to life on Earth. Carbon dioxide is a component of the carbon cycle—the series of reactions of carbon-containing compounds in the biosphere. Within the carbon cycle, processes are interrelated. Cellular respiration, which produces carbon dioxide, and photosynthesis, which uses carbon dioxide, act to maintain a relatively steady amount of carbon dioxide in the atmosphere. Also, recall that carbon dioxide is a greenhouse gas, meaning that it has the ability to absorb thermal energy (heat). By absorbing thermal energy, greenhouse gases prevent the loss of thermal energy into space and, thus, have a direct impact on Earth's climate. Since the industrial revolution in the late 1800s, society has increased its reliance on combustion technologies involving fossil fuels. Higher levels of carbon dioxide emissions are believed to be a major contributor to current changes to global climate. Scientific evidence shows that as the amount of carbon dioxide in the atmosphere increases, the quantity of thermal energy retained also increases. The retention of thermal energy results in an increase in the atmospheric temperature, which, in turn, affects climate and ecosystems.

Practice

2. Refer to the diagram of the carbon cycle on page 157. Explain how the increased use of combustion processes by society and deforestation could result in a higher level of atmospheric carbon dioxide, a level that cannot be removed by natural mechanisms.

3. Use the Internet to research the terms *carbon sink* and *carbon sequestering*. Explain how carbon sinks or carbon sequestering are possible mechanisms for reducing the concentration of carbon dioxide in the atmosphere. Identify how carbon sinks or carbon sequestering would impact the carbon cycle.

Carbon Monoxide

Another oxide of carbon—carbon monoxide, CO(g)—is a common product of combustion. Carbon monoxide is produced when the quantity of oxygen is limited during the reaction process.

$$2\ CH_4(g) + 3\ O_2(g) \rightarrow 2\ CO(g) + 4\ H_2O(g)$$

Carbon monoxide is a product of an incomplete combustion of a carbon compound.

Concern exists over the presence of carbon monoxide in emissions. As a result, its concentration is often measured during environmental monitoring.

Figure B1.3: Mechanics often have to work on an engine while it is operating. To prevent exposure to carbon monoxide, an exhaust vacuum is used.

Carbon monoxide is associated with inefficient combustion processes, which include automobile emissions. Carbon monoxide can pose a threat to your health. In Unit A you discovered that the circulatory system transports oxygen to cells within the body and that this is only possible by the interaction of oxygen with hemoglobin. Because of the similarities between oxygen and carbon monoxide molecules, carbon monoxide is able to compete with oxygen for binding sites on a hemoglobin molecule. When carbon monoxide is present in inhaled air, it binds to hemoglobin, preventing hemoglobin from binding to oxygen. This decreases the amount of oxygen available to the cells in your body, and can result in death. Emissions-testing programs measure the carbon monoxide concentration in vehicle exhaust. These programs can indicate whether maintenance is required to improve the efficiency of an automobile's engine.

A carbon monoxide detector, present in many homes today, provides one means of monitoring combustion processes. A furnace that has poor combustion efficiency not only produces carbon monoxide, a health threat, but also converts less of the potential energy from the fuel it uses into thermal energy. Regular inspection and maintenance ensures the proper operation of a furnace. There is a great deal of concern about maximizing the efficiency of combustion and other energy-conversion processes.

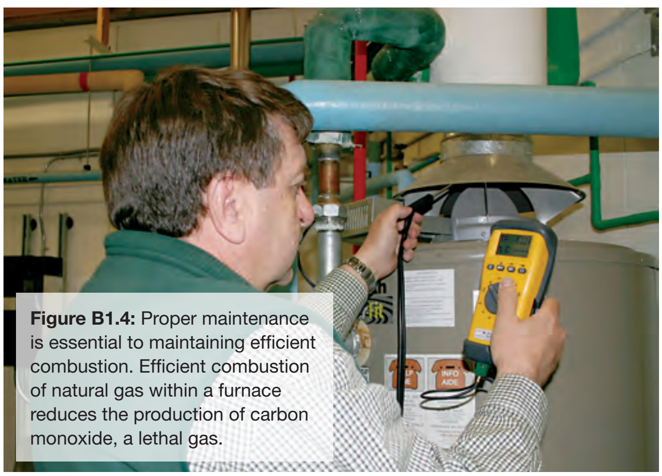


Figure B1.4: Proper maintenance is essential to maintaining efficient combustion. Efficient combustion of natural gas within a furnace reduces the production of carbon monoxide, a lethal gas.

Science Links

Monitoring the efficiency of electricity production can involve more than the detection of by-products, like carbon monoxide. Other monitoring methods involve measuring the power output of the facility. In Unit C you will read more about measuring power and how it can be used to determine the efficiency of the transfer of electrical energy through transmission lines.

DID YOU KNOW?

On average, the concentration of CO(g) in a room may be 0 to 2 parts per million (ppm). Carbon monoxide detectors emit a warning when levels reach 75 ppm to 100 ppm. Expressed as a percent, the detector is set to recognize a CO(g) concentration between 0.0075% and 0.0100%.

Practice

4. Balance the equations representing the complete and incomplete combustions of methane.

complete combustion:

$CH_4(g) + O_2(g) \rightarrow CO_2(g) + H_2O(g)$

incomplete combustion:

$CH_4(g) + O_2(g) \rightarrow CO(g) + H_2O(g)$

5. Use the coefficients from the balanced equations in question 4 to determine the ratio of methane to oxygen in each process. Which reaction uses more oxygen per molecule of methane? Explain how you used the ratios to determine your answer.

Oxides of Sulfur

Sulfur is an element found in small quantities within many of the natural resources burned as fuels. Coal—a fuel commonly used in the production of electricity throughout Alberta and the world—often contains sulfur in varying amounts. Other energy resources, like crude oil and tar sands, also contain sulfur.

Natural gas is another energy source that commonly contains sulfur; but it is in the form of hydrogen sulfide, $H_2S(g)$. The hydrogen sulfide present in **sour gas** is toxic to humans and forms an acidic solution if combined with water. Some sources of sour gas contain more than 30% hydrogen sulfide. Processing natural gas often involves removing the hydrogen sulfide. This is called sweetening. The sweetening process not only reduces the risk to humans in the case of an accidental gas leak, but also reduces the corrosive effects sour gas has on pipelines.

sour gas: natural gas that contains greater than 1% hydrogen sulfide

It is estimated that about 40% of the natural gas reserves in Alberta are sour. Therefore, the removal of hydrogen sulfide is a vital industrial process.

Figure B1.5: Sour gas flare

During the lifespan of a gas well, low-quality natural gas is sometimes released. This low-quality gas—often containing hydrogen sulfide—is flared. Flaring converts hydrogen sulfide into sulfur dioxide and sulfur trioxide emissions.

Flaring Process—
Unbalanced Chemical Equations

$H_2S(g) + O_2(g) \rightarrow SO_2(g) + H_2O(g)$

$SO_2(g) + O_2(g) \rightarrow SO_3(g)$

The combustion of coal also results in the production of sulfur dioxide, although the amount can vary depending on the quantity of sulfur in the coal. The coal mined in Alberta contains less sulfur than the coal mined in eastern Canada. What do you think the effect would have been if sulfur-rich coal were used in the investigation on page 155?

Figure B1.6: Stockpile of sulfur from desulfurization

The yellow stockpiles seen near facilities that process natural resources (e.g., petroleum, oil sand, and very sour gas) consist of elemental sulfur—the product of desulfurization. Sulfur is commonly combined with metal atoms within metal ores. Refining metal ores involves removing sulfur by heating the ore in the presence of oxygen. In eastern Canada, particularly southern Ontario, the refining of nickel and other metals produces sulfur dioxide emissions.

Practice

6. Balance the chemical equations that occur during the flaring process.

Oxides of Nitrogen

You probably already know that Earth's atmosphere is a mixture of many gases. Nitrogen, $N_2(g)$, makes up 78.1% of Earth's atmosphere. Whenever you inhale or whenever air is drawn into an engine to combust a fuel, nitrogen is present. If the temperature of the combustion process is high enough (above 650°C), the normally unreactive nitrogen molecule is activated and will react, often producing nitrogen oxides. The oxides of nitrogen produced by combustion reactions are nitrogen monoxide, NO(g), and nitrogen dioxide, $NO_2(g)$. These are commonly referred to as NO_x compounds.

Production of NO_x Compounds

$N_2(g) + O_2(g) \rightarrow 2\ NO(g)$

$2\ NO(g) + O_2(g) \rightarrow 2\ NO_2(g)$

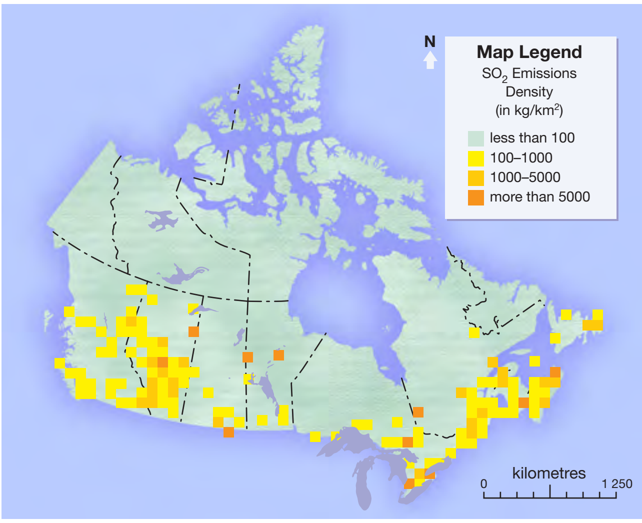
The most common sources of NO_x compounds are high-temperature combustion processes. These include the combustion of hydrocarbon fuels by automobiles and by furnaces used in homes and industry. Studies have shown that higher NO_x emissions occur in urban areas and that NO_x levels can fluctuate daily or monthly depending on the season.

Practice

7. Explain why NO_x emissions are higher in urban areas than in rural areas.
8. For each situation given, predict whether levels of NO_x emission will increase or decrease.
   a. morning and evening rush hour
   b. a cold snap in the winter
   c. a heat wave in the summer months

Chemical Reactions in the Atmosphere

Sulfur Dioxide (SO_2) Emissions in Canada (2000)



Nitrogen Oxide (NO_x) Emissions in Canada (2000)

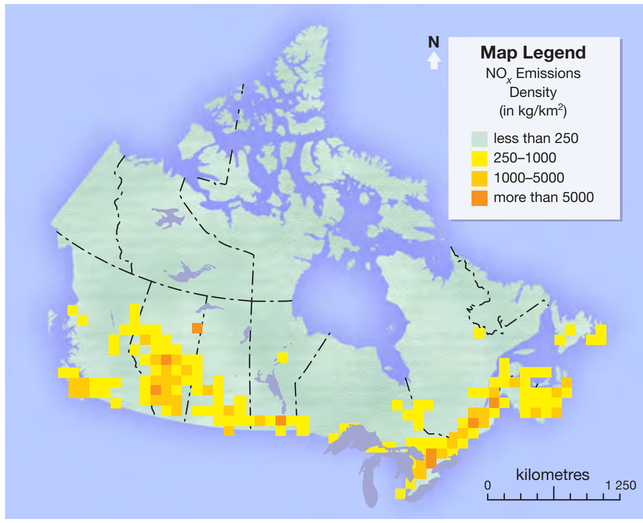


Figure B1.7: Greater emissions of SO_2 and NO_x occur near major Canadian centres.

A list of natural and human activities that produce SO_2 and NO_x is shown in the "Sources of SO_2 and NO_x" table.

SOURCES OF SO_2 AND NO_x

Sources of SO_2	Sources of NO_x
Natural	**Natural**
• hot springs • volcanic outgassing	• forest fires
Human-made	**Human-made**
emissions from • coal-fired power plants • pulp and paper mills • refining crude oil • refining oil sands • refining metals and smelting • automobiles	emissions from • fossil fuel power plants • industrial and domestic furnaces • production of fertilizers • burning of crops • automobiles

Notice that many of these emissions are the result of human activity, with the result that larger emissions occur close to major cities. As you will see in later lessons, Earth's atmosphere can provide suitable conditions for emissions—such as the oxides of carbon, sulfur, and nitrogen—to undergo additional chemical reactions. You will examine the impact that NO_x and SO_2 emissions have on the biosphere. But first, you will see how emissions are monitored in Alberta and who is involved.

Monitoring Emissions in Alberta

Alberta Environment is involved in programs that monitor and maintain the quality of Alberta's environment to protect the health of citizens and ecosystems. Desired standards for environmental quality are determined by the collection of data from scientific, societal, technical, and economic sources. Factors considered when establishing standards for environmental quality include the

- sensitivity of organisms to the presence of substances of concern
- behaviour of substances when in the atmosphere or other parts of the environment
- natural levels and fluctuations that may occur in concentration of substances
- availability of technology to control or avoid emissions
- ability to detect and monitor the presence of substances of concern

Figure B1.8: Alberta Environment's MAML (mobile air monitoring laboratory) is specially equipped to sample and monitor the air in any location throughout Alberta.

In Alberta, air quality is monitored using data collected by monitoring stations operated by industry and the provincial and federal government. Currently, you are able to use the Internet to access information about air quality throughout the province. Depending on the location of the monitoring stations in your immediate area, you may be able to view the concentrations for a variety of substances that are used to determine air quality in the area immediately near your school or home.

Alberta Environment also uses a mobile monitoring system to perform measurements of air quality. View the segment "Mobile Air Monitoring Labs (MAML)" on the Science 30 Textbook CD for additional information about the mobile monitoring system.

Metals and Metal Oxides

Metal atoms, either in their elemental form or as a compound, can also be present in emissions from processes that rely on combustion reactions. For example, coal may contain small amounts of metals, like lead or mercury. When coal is combusted, these metals may be carried great distances before depositing on the ground. Monitoring processes pay close attention to the detection and measurement of the concentrations of heavy metals, like lead and mercury, in emissions and elsewhere in the environment, especially since these metals have been known to adversely affect human health.

Particulate Matter

A higher incidence of asthma and other respiratory diseases occurs in populations of individuals exposed to higher levels of particulate matter. Particulate matter consists of solids suspended in the atmosphere that come from natural and human-made sources. Soot, smoke, and ash produced by either industrial processes or forest fires; soil particles; and pollen are examples of particulate matter that may irritate parts of the respiratory system. Cigarette smoke is an especially dangerous source of particulate matter because it contains organic compounds (e.g., benzene) that are **carcinogens**. You will learn more about organic compounds in Chapter 2 of this unit.

carcinogen: any agent that causes the likelihood of cancer to increase

Many carcinogens are also mutagens.

Utilizing Technology

Taking a Stand—Emissions Testing

Albertans have a high dependence on the cars and trucks they drive for pleasure or for work. In addition, Albertans enjoy their recreation vehicles (e.g., motorcycles, quads, boats, and snowmobiles). Albertans also place a high priority on their health and the health of the diverse habitats that exist throughout the province.

Science Skills
- ✓ Performing and Recording
- ✓ Communication and Teamwork

As you know, pollution from vehicles affects both society and the environment. Is it time to place standards on the emissions from vehicles? Currently, three Canadian provinces—British Columbia, Ontario, and New Brunswick—have emissions-testing programs for vehicles. Should Alberta be next?

Purpose

You will debate the following question:

Should Alberta have an emissions-testing program for vehicles similar to those used in British Columbia, Ontario, and New Brunswick?

Background Information

Before you begin, use the Internet to answer the following questions.

1. Why is emissions testing required in some provinces and not in others? In provinces that have emissions-testing programs, are all vehicles tested in all regions of the province?
2. Identify the reason for initiating emissions-testing programs in these provinces.
3. List the items being tested for during an emissions test.
4. What do emissions tests cost consumers in the provinces with testing programs?

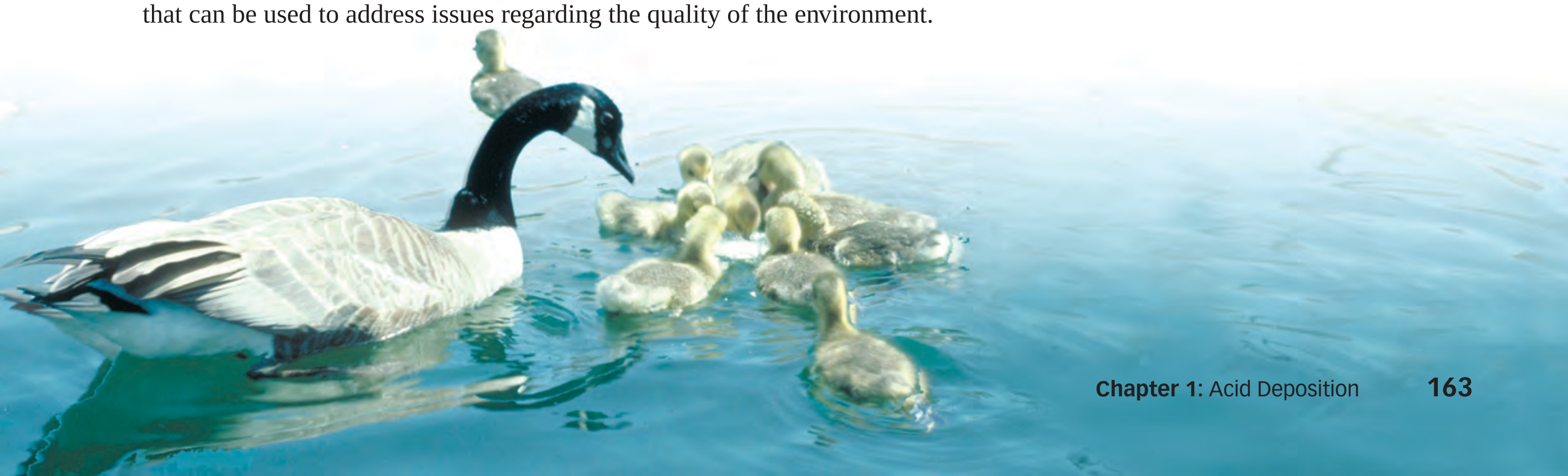
Procedure

5. Prepare a position statement that clearly defines whether you support or do not support mandatory emissions testing of all vehicles in Alberta. When developing your position statement, review the list of perspectives listed on page 590. Use this list to help justify your position.
6. Prepare a rebuttal—a second statement that responds to a criticism of your position. When preparing your rebuttal, imagine you are the opponent in the debate. What part of your position statement would your opponent most likely challenge? Would it be the credibility of the information you present or the conclusions you make? Your rebuttal is your opportunity to develop a plan to further defend your position.

1.1 Summary

Combustion processes, both complete and incomplete, involve a reaction with oxygen that results in the formation of oxide compounds. Some of the oxides produced include carbon dioxide, carbon monoxide, sulfur dioxide, and NO_x compounds (e.g., nitrogen monoxide and nitrogen dioxide). Other emissions that can result from combustion processes include heavy metals and particulate matter.

Because emissions react with elements in the atmosphere that may affect humans and other organisms, monitoring programs have been implemented to measure emissions from combustion processes. These programs provide information that can be used to address issues regarding the quality of the environment.



1.1 Questions

Knowledge

1. Define each term, and describe its significance to this lesson.

a. combustion
b. oxide
c. pollution
d. greenhouse gas
e. hemoglobin
f. sour gas
g. NO_x
h. particulate matter
i. carcinogen

2. Describe, at the atomic level, what happens to the molecules in a fuel during combustion.

3. "The products of a combustion reaction are dependent on the substance being combusted." Explain the meaning of this statement, and include an example.

4. Explain why nitrogen oxides are often referred to as NO_x.

5. Natural gas is a collection of hydrocarbons. Balance the combustion reactions for three hydrocarbons often found in natural gas.

a. $\_\_ CH_4(g) + \_\_ O_2(g) \rightarrow \_\_ CO_2(g) + \_\_ H_2O(g)$

b. $\_\_ C_2H_6(g) + \_\_ O_2(g) \rightarrow \_\_ CO_2(g) + \_\_ H_2O(g)$

c. $\_\_ C_3H_8(g) + \_\_ O_2(g) \rightarrow \_\_ CO_2(g) + \_\_ H_2O(g)$

Applying Concepts

6. Gasoline is a mixture of hydrocarbons, none of which contain nitrogen. Explain how the combustion of gasoline in automobiles can be considered to be a major source of the production of NO_x compounds.

7. The Claus process can be used to remove hydrogen sulfide from sour natural gas. The Claus process occurs in two steps:

1) Thermal Step

$H_2S(g) + O_2(g) \rightarrow S(s) + H_2O(g)$

$H_2S(g) + O_2(g) \rightarrow SO_2(g) + H_2O(g)$

This step occurs in a furnace at high temperatures.

2) Catalytic Step

$H_2S(g) + SO_2(g) \rightarrow S(s) + H_2O(g)$

a. Balance the three reactions in the Claus process.

b. Identify one emission, other than those listed in the equations, that is produced by the Claus process.

c. Improvements to the Claus process focus on reducing emissions. One improvement requires the use of pure oxygen rather than atmospheric air in the furnace. Explain how the use of pure oxygen could result in a reduction to emissions from the Claus process.

8. Prepare a table that summarizes the similarities and differences between the properties and processes that result in the formation of the carbon, nitrogen, and sulfur oxides described in this lesson.

9. Obtain the handout "NO_x and SO_2 Emissions in Canada (2000)" from the Science 30 Textbook CD.

a. Use the information from each map to prepare a table that identifies the locations in Alberta where emissions of SO_2 and NO_x are moderate and high. Provide a reason as to why emissions are moderate to high.

b. Identify a location in Alberta with high levels of NO_x emissions and low levels of SO_2 emissions. Explain how this situation could exist.

c. Use the Internet to obtain information on other locations in Canada where SO_2 and NO_x emissions are relatively high. Add this information to your table in question 9.a.

10. In 2000, emissions of SO_2 in Canada were estimated to be 2.4×10^6 t (tonnes). Prepare a table that shows the mass of sulfur dioxide emissions from each of the sources shown in Figure B1.9.

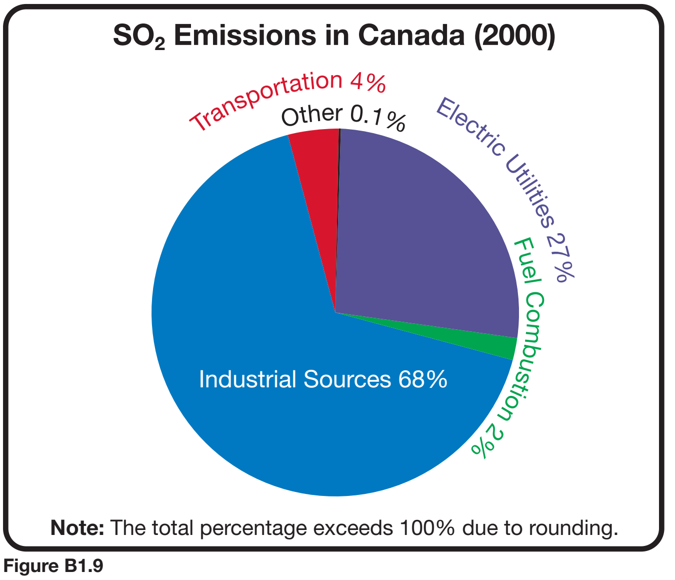


Figure B1.9